Additive Technology Methods for Manufacturing Permanent Magnets

Dmitry Efremov¹, Alla Gerasimova^{1,}, Nikita Kislykh¹, and Cristina Shaibel¹*

¹National University of Science and Technology "MISIS", street the Lenin prospect,4,Moscow,119049, Russia

Abstract. The paper presents the results of studying the possibility of using the selective laser melting method for production of permanent magnets. This process allows to manufacture not only product models and prototypes, but also finished functional products by adding material layer by layer and bonding particles and layers to each other. We have considered the application areas of selective laser melting (SLM) based on powders obtained by different methods for the study. In addition, we have analyzed the traditional magnetic alloy casting technology, studied magnetic materials, and compared the powder magnet properties with standard data. We have found that the parameters of powders obtained by gas atomization are qualitatively superior to those of powders obtained using other methods, whereas the resulting magnets meet the requirements for magnets. Based on the 25Kh15KA alloy powder atomized by gas atomization, a SLM plant allows to manufacture permanent magnets with a material density of 7.59–7.55 g/cu.cm, which meets the requirements recommended by the State Standard GOST 24897-81, and to obtain the magnet properties that can be achieved using traditional metallurgical technologies.

1 Introduction

The process of selective laser melting is one of the promising production technologies. SLM processes allow to manufacture not only product models and prototypes, but also finished functional products by adding material layer by layer and bonding particles and layers to each other. The use of this method is considered a priority, if the product geometry cannot be provided using any of the existing methods of material processing; if the pre-production time would significantly slow down the prototype manufacture; or if the loss of expensive raw materials should be avoided. Additive technologies are considered an alternative to existing traditional subtractive processing methods, such as mechanical, electrophysical, and electrochemical methods. In contrast to traditional methods of shaping, when casting defects are “cut or polished” from the workpiece when creating a part, using the SLM method, the part is “built up” from a pre-produced powder material, which is applied layer by layers; particles melt to form a layer of molten particles; particles and

* Corresponding author: gerasimova.aa@misis.ru

layers are bond to each other. This technology allows the synthesis of unique products with an internal hollow surface, such as heat exchangers with a complex structure of cooling channels; casting molds for creating various models; and mesh filters. This technology allows for manufacturing products with a rectangular or another complex shape of internal cavities, for example, a spiral one.

Currently, the SLM technology is one of the most promising and actively developing methods of additive manufacturing. This method was created due to the accelerated development of prototyping technologies in late 20th century [1–10].

SLM allows to produce not only demonstration samples and product models, but also functional finished products by adding material layer by layer and bonding particles and layers to each other using well-known methods. Our studies of samples produced using this technology have shown that, in terms of their physical and mechanical properties, they are not inferior to parts made using traditional casting technologies [11–16].

The SLM technology allows for manufacturing parts of a rectangular or other shape of internal cavities (e.g., spiral) or any other shape with a mesh filling. The modern development of these technologies suggests that, in a short time, a new equipment will be available to allow the manufacture of multicomponent products of various chemical, granulometric, and morphometric composition. For example, the body of a part can be made of structural steel, whereas the inner cavity can be made of copper alloys for products such as heat exchangers [17–21].

2 Objects and methods of research

The goal of this research is to study the possibility of making permanent magnets from the material of the Fe-Cr-Co system using selective laser sintering methods.

The operation principle of a plant for additive manufacturing using laser radiation can be explained as follows. The powder coating and leveling device removes the powder layer from the feed and distributes it evenly over the substrate surface. Next, a laser beam selectively scans the powder layer surface and forms the product by melting or sintering. After scanning the powder layer, the platform with the manufactured product is lowered by the applied layer thickness, whereas the platform with the powder is raised, and the powder layer applying and scanning process is repeated. At the end of this process, the moving mechanism with the product is lifted and the product is cleaned of unused powder material. Figure 1 shows a flow chart of the additive manufacturing technology based on layer-by-layer sintering of powder materials by a laser beam using mathematical CAD models.

This technology allows to manufacture finished products of complex shapes [22–30].

Wettability, surface tension, and melt viscosity play an important role in the product manufacture [31–34]. A factor that prevents the use of various metals and alloys for SLM is the “spheroidization” effect manifested in the formation of separately lying drops, rather than a solid melting trace. The reason for this effect is the surface tension: the melt tries to reduce the free surface energy, creating a shape with a minimum surface, that is, a sphere.

Carbon steel is one of the most interesting materials for additive manufacturing: it features a low cost and excellent mechanical properties. An increase in soluble carbon content in steel improves its fluidity and wettability. This allows the use of the first simple products containing 0.6–1% of C with a density of 94–99% [35], and when using pure iron, the density is only about 83%. During selective laser melting of carbon steel, the melting trace solidifies upon rapid cooling, with a sorbitol or troostite structure formed. In this case, due to thermal stresses and structural transformations, significant stresses occur in the metal, that can lead to cracking or the product deformation.

Fig. 1. Selective laser melting process flow chart

Product geometry is also important, because cracks are caused by abrupt transitions, small radii, and sharp edges. If, after such “printing”, the steel does not have a certain level of mechanical properties and needs additional heat treatment, we should take into account the previous shape constraints to avoid hardening defects. This reduces to some extent the prospects of using SLM for carbon steels.

In the manufacture of products using the traditional method, one of the ways to avoid cracks and webs when hardening products of complex shapes is the use of alloy steels, where the alloy slows down the transition to austenite upon cooling (in addition to improving physicochemical and mechanical properties), which reduces the critical hardening rate and increases the alloy steel calcination. Due to such low critical quenching rate, steel can be cast in oil or cooled in air, which reduces internal stresses. However, due to rapid heat dissipation, inability to adjust the cooling process, and the presence of carbon in alloy steels, this method does not allow us to avoid significant internal and external stresses during SLM.

Due to the above properties, martensitic steels (MS 1, GP 1, PH 1) are used for SLM, where hardening and increase in hardness are achieved through the release of dispersed intermetallic phases during heat treatment. This allows complex products to be manufactured using SLM and heat treated without the risk of cracking or deformation [36-38]. It should be noted that the manufacturing methods for various types of magnets are fundamentally different.

Iron-chromium-cobalt alloy magnets are manufactured by casting. The most common method of forming such magnets is lost-wax casing or casing in ceramic models. Depending on the required properties, these magnets are made with a columnar (grains are stretched in one direction) or uniaxial structure. After pre-treatment, the magnets are subjected to special heat processing operations: high-temperature treatment, quenching, thermomagnetic treatment, and tempering. As a result, workpieces have a magnetic material structure and become permanent magnets after final grinding and magnetization.

Powders of the 25Kh15KA composition for the manufacture of permanent magnets using the SLM method have been made from a mixture of Fe, Co, Cr powders by gas atomization.

The properties of powders obtained by gas atomization (high sphericity, particle size distribution) are qualitatively superior to those of powders obtained by other methods and meet the requirements for SLM.

In a vacuum melting chamber with a bottom drain, the metal is melted and overheated to the atomization temperature (see Fig. 2). After creating an overpressure in the melting chamber and lifting the stopper, the metal is drained through a heated tube into an atomization chamber. After entering the working part of a nozzle, the metal is atomized with an argon flow (from 40 to 70 atm.) forming dispersed spherical granules; flying in the gas flow through the volume of an atomization column, the powder particles are cooled and enter a receiving cone. Then, they are poured into a primary hopper through a ball valve. Part of the most dispersed powder, which is in a suspended state, does not have time to settle on the cone and chamber walls and, together with the argon flow, these particles fly out through an outlet pipe. Then, they enter a cyclone that separates the powder, which is poured into a secondary hopper. The resulting powder is subjected to gas-dynamic separation and sieve screening in order to isolate the required fraction, depending on the powder purpose.

Fig. 2. Gas atomization process flow chart

3 Results and discussions

Preliminary experiments have shown that a SLM plant allows for manufacturing permanent magnets with a material density of 7.59–7.55 g/cu.m from the 25Kh15KA alloy powder obtained by gas atomization, which meets the requirements of recommended by GOST 24897-81 and the corresponds to the magnet parameters obtained using traditional metallurgical technologies.

These samples have been manufactured at the production facilities of Kurchatov Institute R&D Center as part of the NIO-35 process complex. The plant used for creating a sample of magnetic hard substance based on the Fe-Cr-Co system using the selective laser melting is an EOSint M270 selective laser smelting (SLS) plant.

To study the magnetic and physical properties, we have manufactured four samples with the same cubic geometry. In the manufacture of each of the tested samples, we have chosen different operating modes of the plant, namely:

1. 1,100 mm/s; 195 W;
2. 1,013 mm/s; 189.5 W;
3. 800 mm/s; 150 W;
4. 906 mm/s; 170 W,

where mm/s is the scanning speed and W is the laser power.

The appearance of the samples before machine working is shown in Figure 3.

Fig. 3. SLS samples based on the Fe-Cr-Co system

To create the geometry required for the samples, we used machine working.

The sample density according to hydrostatic weighing: $\rho \sim 7.587\text{--}7.554$ g/cu.cm (99 % of the value recommended as per GOST 24897-81).

The magnetic hard material parameters have been measured using an EM8-6 DC hysteresis graph as per GOST 8.268-77.

The magnetic induction B_r has been measured using a RSh1-10 milliteslameter in an EeI.659.00-43 measuring instrument.

The measurement results are presented in Table 1.

Table 1. Results of measuring the material magnetic properties.

Sample No.	Mode	H_{CB} , KA/m	B_r , T	$(BH)_{max}$, KJ/cu.m
1	1,100 mm/s; 195 W	45.4	1.020	2
2	1,013 mm/s; 189.5 W	45.9	0.981	22,1
3	800 mm/s; 150 W	46.1	0.997	23,6
4	906 mm/s; 170 W	44.8	0.944	21,2
GOST 24897-81		40	1.2	3

In the above table, H_{CB} is the inductive coercive force, B_r is the residual induction, $(BH)_{max}$ is the maximum magnetic energy.

4 Conclusions

1. The properties of powders obtained by gas atomization (high sphericity, particle size distribution) are qualitatively superior to those of powders obtained using other methods and meet the requirements for SLM.
2. Based on the 25Kh15KA alloy powder obtained by gas atomization, an SLM plant allows for manufacturing permanent magnets with a material density of 7.59–7.55 g/cu.cm, which meets the requirements recommended by GOST 24897-81 and corresponds to the properties of magnets manufactured using traditional metallurgical technologies.

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